D]LI'PO EXPRESS: ADVANCED TECHNOLOGIES ENABLE LOWER COST M1SS1ONS '1'0 THE OUTER SOLAR SYSTEM AND BEYOND

Robert L. Staehle, Leon J. Alkalai, E. Jay Wyatt
Jet Prepulsion Laboratory
California Institute of Technology
4800"0211< Grove Drive
Pasadena, CA 91109-8099
(818)354-1176

John Dohoney
Interface and Control Systems
8945 Guilford Rd.
Suite 120
Columbia, MD 21046
(301) 596-2888

Abstract

Missions to Pluto and the outer Solar System are typically driven by factors which tend to increase cost, such as: long life, high radiation exposure, a large power source, high AV requirements, difficult telecommunications links, low solar illumination at the destination, and demanding science measurements. Advanced technology is a central part of responding to such challenges in a manner which permits the cost of development and operations to be an order of magnitude less than for prior outer planet missions. Managing the process of technology planning and advanced development versus the associated cost and mission risk is a formidable challenge. Outer Solar System /Europa/Pluto/Solar Probe development activities are leveraging the latest products from the industry, government lab and academia technology pipeline in the areas of software, low power integrated microelectronics, low mass, high efficiency radioisotope power if used, and telecommunications. This paper summarizes the current technology development plan, which is tightly coupled to the New Millennium Program (NMP) *Deep Space 1* technology validation flight. Specific detail will be presented about advanced microelectronics technology. This technology will also be shown in the context of an on-going technology roadmap that extends beyond the Pluto Express mission. Other details focus on new technologies available for low cost mission operations, and the processes required to best develop and utilize these technologies. The development goal is to create an integrated flight and ground system with the functional simplicity necessary to achieve high reliability, operability, and a low total mission cost. The development process leverages the JPL Flight System Testbed and commercial off-the-shelf (COTS) products. A university partnership provides additional development support and is leading to a partnership for operations. Software technologies for spacecraft self-commanding and self-monitoring play a key role in meeting an operations vision called Beacon Monitoring. This approach is expected to decrease operations cost significantly by reducing the amount of routine interaction with the spacecraft. The experience gathered may be valuable to Earth orbiting missions, the Mars Exploration Program, and Mission to Planet Earth.

INTRODUCTION

The application of NASA's *faster-better-cheaper* initiative can clearly be found in the design of the Outer Solar System planetary spacecraft to Pluto (Staehle, et al. 1992 and Price, et al. 1996) or Europa, which plan to achieve ambitious scientific objectives at a fraction of the cost of previous deep-space missions (Dyson 1995). This can only be achieved by major changes in the way the spacecraft is designed, managed, and operated, as well as in the way advanced technology is inserted into the flight and ground system. Advanced technology planning, technology development, validation and insertion play a more prominent role in the mission design and pre-project phase. Dramatic reductions in mission life-cycle cost may be achieved by leveraging the on-going national technology pipeline from industry, academia, other national laboratories, as well as from small businesses. An Outer Solar System technology roadmap that is consistent and aligned with a corresponding commercial technology roadmap is of mutual benefit to both the commercial sector as well as to space science.

Two specific technology areas will be discussed in more detail in the remainder of Ibis paper: advanced microelectronics technology and advanced software engineering. Consider the case of advanced microelectronics technology for low-power highly reliable and highly integrated systems. This technology is crucial for the reduction of all spacecraft electronics into a single integrated functional system that will dramatically reduce the spacecraft mass, volume, and power consumption. This will in return, reduce the total spacecraft and launch vehicle cost.

Moreover, this technology will also be of great benefit to the fast growing mobile and portable computing and global communication commercial industry. Technology transfer and insertion will occur in both directions, thus creating a synergy that will give a new meaning to NASA as a national leader in technology development that also stimulates the commercial industry. The second technology area discussed in this paper in more detail is software engineering for highly reliable real-time applications, Because deep-space missions have to perform reliably over very long periods of time, software techniques will be developed for systematic and scheduled software upgradability as new techniques and algorithms are developed on ground. Software techniques currently under research and development, for software self-]l]:li]ltcllallcc and self-tcpnir, fault-protection and self-Tll:itl:Igct]lcrll, may become mature significantly after launch and yet timely for flight encounter. The development of such advanced intelligent and adaptive software systems could benefit the fast growing world-wide-web (WWW) browsing and search tools for future ()]]-line information systems. Software that can perform reliably in the presence of failures, buys, glitches, changing configurations, and numerous asynchronous events will be of significant benefit to both low-cost space exploration as well as to the ground-based distributed information systems.

In the following sections, we first briefly describe the current approach for technology planning used by the Pluto Express mission which is relying 00 technology validation by the New Millennium Program *Deep-Space* 1 mission (Casani and Wilson 1995), to be launched in July 1998. We describe some of the technologies being planned within the area of advanced microelectronics systems, followed by technology that is planned under advanced software engineering.

TECHNOLOGY PLANNING FOR ACCELERATED INSERTION INTO FLIGHT

We outline a phased approach towards the accelerated insertion of advanced spaceborne technology into target missions. By *advanced*, we imply technologies that enable more than incremental improvements to the state of the art; that is technologies (trot represent a significant step forward. These advanced technologies would otherwise not easily make their way into future missions without a dedicated technology validation program such as the New Millennium Program. The three phases prior to technology insertion, shown in Figure 1, ate:

1. Advanced Technology Development (ATD)
2. Early Flight Experimentation
3. Technology Validation

The difference between early flight experimentation and flight validation is that an experiment is usually a non-essential element of the mission and is not in any critical path. On the other hand, technology validation implies that the new technology is being validated not just by the fact that it is being flown io space, but (hat it is performing its intended function within the actual mission.

Technology Development

Technology development planning must strongly leverage the on-going national technology pipeline, and seek to establish early partnerships with other government agencies that have on-going technology development programs. For example, the Defense Advanced Research Projects Agency (DARPA) has an on-going program in Ultra Low Power Electronics; Department of Energy (DOE) has an advanced program in Radioisotope Power Sources (RPS).

Early Flight Experimentation

Early flight experimentation should be applied to the very high-risk technologies that are still in the early stages of development, and which would significantly benefit from exposure to a realistic radiation environment. Not every new technology needs to go through experimentation. Moreover, not every new technology needs validation only in space; that is some may be validated on the ground via testing, environmental stress, or even radiation testing.

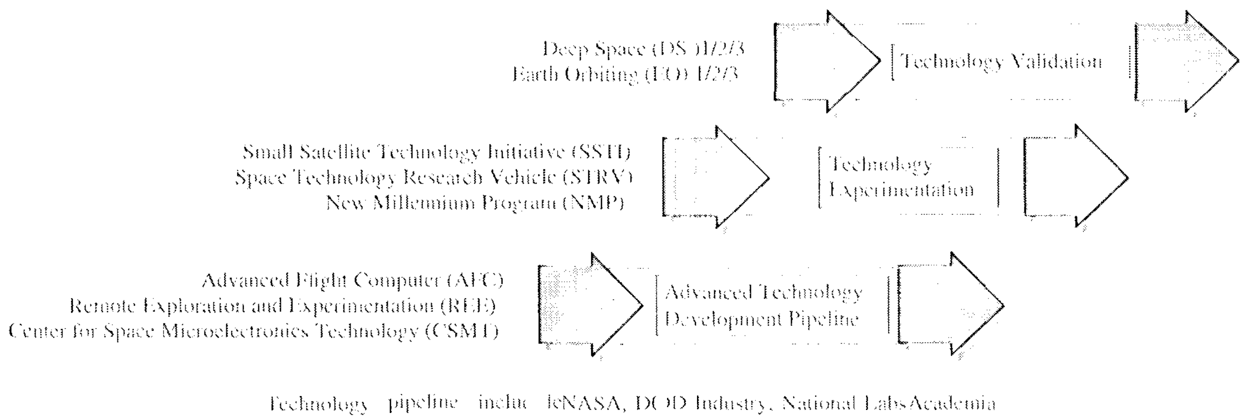

FIGURE 1. Prior to Advanced Technology Insertion into a Target Project, a New Technology is First Developed to the Point of Early Flight Experimentation, Followed by Flight Validation.

Technology Validation

Technology validation represents the final and perhaps most important step prior to technology insertion. Not only is this phase intended to validate the technology, but it can also provide for the non-recurring engineering requited to reduce the total cost 01" the target mission, In the case of the Pluto Express mission, it is highly leveraging the currently planned New Millennium *Deep-Space 1* spacecraft, which **will** launch **in** July 1998. The process of technology selection for validation on the New Millennium flights is partially determined by the science objectives in the 21st century and in part by the immediate needs of projects (in the new millennium) that are actual customers. In the case of Pluto and the New Millennium Program, regular status meetings are held to coordinate technology" validation and technology insertion. A snap-shot of this technology negotiating list is shown in '1'able 1 below.

PLUTO EXPRESS MICROELECTRONICS TECHNOLOGY

The current Pluto Express technology plan includes the aggressive insertion of advanced microelectronics technologies into its baseline mission. These include:

- Advanced microelectronics packaging technologies such as standard sized Multichip Module (MCM) packages, 3D chip stacking, and 3D MCM stacking, for a highly integrated functional system (Teneketges and Alkalai 1994).
- Advanced low power techniques, including low-voltage, micro-power management, highly integrated solid state power switches, high-efficiency power converters, etc.
- Reliable and radiation tolerant commercial technology (where applicable) combined with radiation hardened technology for critical applications, such as the central processing unit (CPU) (Underwood and Alkalai 1996).
- Component level redundancy to increase system level reliability while still maintaining a highly integrated, low-mass, and low volume avionics system.
- High performance computers with scaleable clock rate and power consumption, that can operate in dual lock-step mode as a hot back up or as a cold spare.
- The use of only standard interfaces and where possible commercially successful standards, such as the PCI (or HighRel PCI) local bus, JTAG bus for real-time testing, standard serial buses, (Alkalai et al. 1996) etc.

In Figure 2 we show a graphical representation of the 3D flight computer that is being validated by the New Millennium *Deep-Space* 1 mission. 11 consists of a 4 layer 3D MCM stack of 'slices' that contain a 50-MHz Rad6000 ['1'11, 400" Mbytes of dynamic memory, 128 Mbytes of non-volatile memory, and a fiber-optic 20-MHz serial bus. The *Deep Space 1* mission will also validate two additional technologies of great importance to the Pluto Express mission: The Ultra Low Power Experiment that consists of ().18 micron feature size 1.() volt CMOS S01 technology (fabricated at MIT/LL and **sponsored** by DARPA); and the Power Activation and Switching Module (PASM) that is being developed ***jointly by*** Boeing, Lockheed Martin and co-sponsored by the Pluto Express Advanced Technology Development program.

TABLE 1. New Millennium DS1 Technology Priorities and Benefits to Pluto Express.
Note: The New Millennium development probabilities represent current plans to Deep Space 1 (DS 1) flight, but are subject to change.

Technology Requirements	Dvmt. Probablitiy	Benefit to Pluto	Remarks
Autonomy			
Autonomy Remote Agent	High	High	
Beacon monitor EEMOS & Testbed (w/self-command/monitor, etc.)	High	High	Would be a very high benefit if Pluto rqmts. are met.
Cruise Optical Navigation & Control	High	Low	
Cruise Optical Navigation & Control w/SEP	Medium	Low	Gravity assist is more cost effective than SEP for Pluto 2001 to 2005 launches
Celestial Sensor	Low	High	
Microelectronics			
AEC & Stacked MCM	High	Highest	
RAD6000-5L in Advanced Flight Computer	High	High	Dvmt. tools and experience are benefits of this chip over the RH-32
Flash Memory SSR (with S/W drivers)	High/Med	Medium	Useful as backup storage but not as SSR due to write time rqmts.
Power Microelectronics	High/Med	Highest	
Battery Control Electronics	Low	None	
High Speed S/C Fiber Optics Data Bus	Low	Low	Power requirements are a concern for Pluto
Propulsion Valve Driver Elect. MCM	Low	High	
Power PC chip in Advanced Flight Computer	Low		May be available after NMP Flt. #1
MEMS Experiment Electronics			
Instruments & Micro-Electro-Mechanical Systems (MEMS)			
Adv. Multi-Spectral Imaging Spectrometer	High	High	
Active Pixel Sensing Camera	Low	Medium	
μ-Gyro	Low	High	
Modular Architectures & Multifunctional Systems			
Penetrator	Low	None	
Inflatable Antenna	Low	None	
Lithium Ion Battery	Medium	None	
Multifunctional Structure	High	Low	
Pulsed Plasma Thrusters (Mark 1)	Low	None	Power useage is a concern for Pluto
SCARLET Array	High	None	
Process Millennia	Low		
Modular Chemical Propulsion	Low	Low/Med	
Silicon Carbide Instrument Structure	High	Med/High	
Silicon Carbide Bus Structure	Low	Low	
Communications Systems			
Tiny Exciter	Low	Med/Low	
Ka or X-band SSPA/EPC	High	Highest	
Low Mass Antenna	Low	High	
Phased Array/High Rate Modulator	Low	None	
Optical Communications Downlink	Low	Med/Low	Concerns about ground infrastructure and emergency comm link
SDST (supplied by flight team)	High	Highest	Being developed with Mars consortium.
Other Technologies Needed for Pluto			
Advanced Radioisotope Power Source	Very Low	Highest	NASA/DOE Development NOT A NEW MILLENNIUM DVMT
Advanced Miniature Propulsion Components	Very Low	High	
Advanced Composite Propellant Tanks	Very Low	High	

PLUTO EXPRESS SOFTWARE AND AUTONOMY

Successful development of mission software is a formidable challenge for upcoming NASA missions with substantial onboard autonomy. Complex software systems, even those developed by reputable organizations, have had a tendency to fail. Recent software development nightmares, such as the Denver International Airport baggage handling system and the Ariane 5 failure remind us of this problem. Early in the life of the project, the Pluto Express team began taking critical steps to minimize cost, schedule, and technical risks associated with mission software.

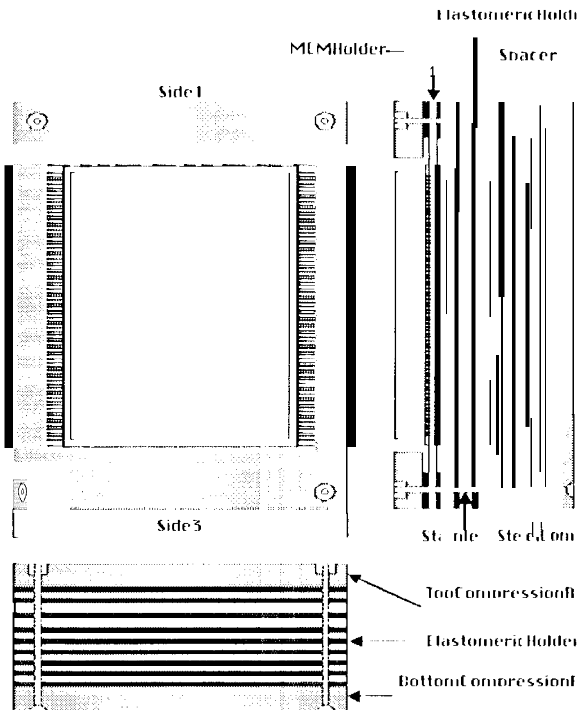

FIGURE 2. 3D Flight Computer To Be Validated By The NMP *Deep Space 1* Mission.

Design and Development Approach

At the highest level, the approach taken in developing Pluto Express software is influenced by a vision for a highly modular system software architecture that can be easily configured for a given mission. Transitioning this vision into reality requires that a development methodology and architecture evolve for Pluto Express that closely parallels the directions of the commercial sector today. Methods for constructing applications by assembling re-usable software components have emerged in industry as a highly productive and widely accepted way to develop custom applications. Use of tools such as Java facilitate development of a component-based, compact, and platform-neutral software architecture for flight and ground systems. The Pluto Express testbed approach provides a means for investigating these and other exciting approaches for low cost development, low cost operations, and maximum reusability.

The design vision for Pluto Express system software also involves creating highly robust, operable, autonomous, integratable and evolvable end-to-end system for outer planet missions. Emphasizing robustness is necessary given that the primary motivation for the mission is to return science data. Designing for operability and autonomy is important to stay within mission operations cost constraints. Frequent and early integration lowers overall development cost by resolving design disconnects early in the design process. Designing for evolvability ensures that adequate margins exist and that the overall software architecture can support post-launch software upgrades throughout the long cruise period.

At the working level, there are several ways in which the Pluto Express team is meeting the challenge of developing a successful software system. A software management philosophy has been adopted that is based on [illegible] methods for minimizing risk throughout development. A project team approach to concurrent engineering of hardware, software, and mission operations is improving the overall mission design. Extensive testbedding early in the development process is also resulting in a better design and is a means for early evaluation of potential software technologies. Virtually all project testbedding (hardware and software) has been coordinated by the software primary accountable team member to place further emphasis on the importance of software to the overall mission design.

New Technology Insertion

Pluto Express has precipitated development of autonomous spacecraft at JPL. Much of what the New Millennium Program has become in the area of onboard autonomy was shaped with input from the Pluto Express team. The Beacon Monitor technology (Wyatt and Carraway 1995) was conceived from Pluto Express team members in response to the need to reduce telemetry tracking during cruise. With this technology, flight software will select one of four subcarrier frequencies to notify low-cost ground antennas the urgency with which the spacecraft needs to be tracked for engineering telemetry during cruise. When the tone indicates that tracking is required, the spacecraft will summarize onboard conditions since the last pass and will downlink "intelligent" summaries. Engineering data summarization and "beacon monitor" operations are being demonstrated on NMP DS-1 to validate the technology for full-up use on Pluto Express.

The as-launched design will have significant new technology content to meet initial requirements for low cost operations. Pluto Express testbed prototypes already contain the latest versions of software for commercial spacebourne operating systems, telemetry management, and interprocess communication. An on board executive, with heritage from New Millennium Program DS-1 software or Interface & Control System's SCL (Spacecraft Command Language) will be used. In addition to adapting the latest products, the as-launched software configuration will contain new techniques for onboard data summarization, beacon monitor operations, and new approaches to fault protection (including protection against *software* failures).

At encounter, from a technology standpoint, the mission can only be exciting in software. The hardware will be old, but will be designed to accommodate substantial new software during the long cruise period. Several additional technologies are being investigated for post-launch migration into the flight system architecture. These include automated cruise science, onboard planning, and autonomous maneuvers. Payoffs could include increased science return and lower operations cost with little or no increase in mission risk. The results from these investigations may drive the overall flight and ground system design.

Full Mission Simulation

Mission development efforts prior to Phase C/D will culminate in a full-mission simulation capability. The ability to "lose the mission" over and over again in simulations is critical for evaluating the effectiveness of the end-to-end design. New software technologies will be validated pre-launch and the effectiveness of fault protection software will be assessed. Figure 3 provides an overview of the components of a full mission simulation.

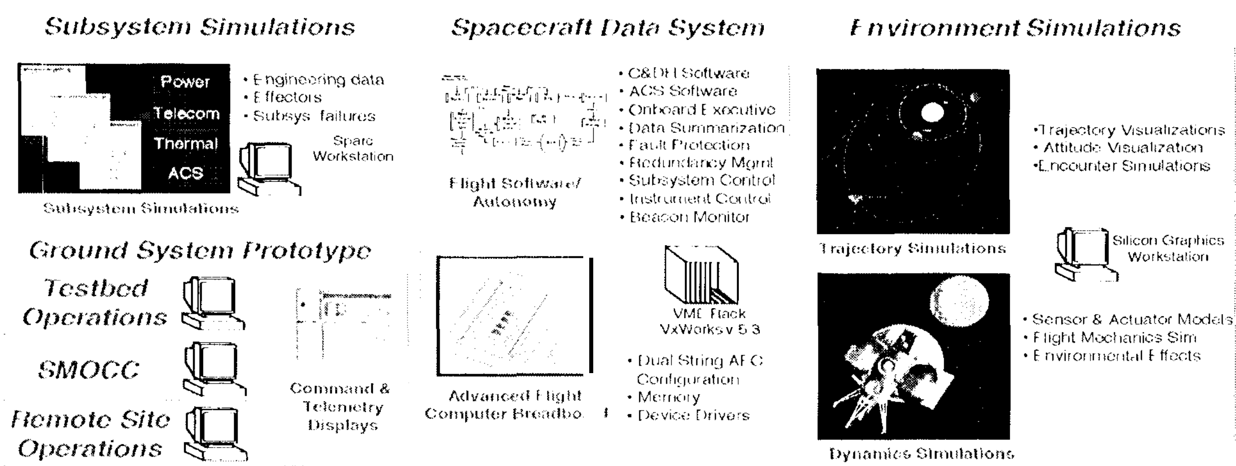

FIGURE 3. Full Mission Simulation Components (SMOCC = Simulated Mission Operations Control Center).

Development Environment

Pluto Express early system development is being performed at the Jet Propulsion Laboratory in the Flight System Testbed (FST) and in a testbed located at the University of Colorado Space Grant Consortium. The JPL FST is a facility shared by new flight projects and also serves as a repository for COTS and government software products. The FST is an excellent environment for technology sharing and leveraging of external efforts. Pluto Express is also capitalizing on lessons learned from other users of the facility. The testbed at U. Colorado was funded by Pluto Express to develop components of the End-to-end Mission Operations System (EEMOS). The two testbeds have been configured to support distributed development of mission software.

In FY96, the testbeds were configured as shown in Figure 4 to investigate issues associated with distributed development and operations. In this configuration, commands were sent from a prototype ground station at U. Colorado to a target processor running flight software prototypes at JPL. Subsystem simulations, also running on computers at JPL, produced subsystem telemetry that was passed back to U. Colorado as simulated telemetry.

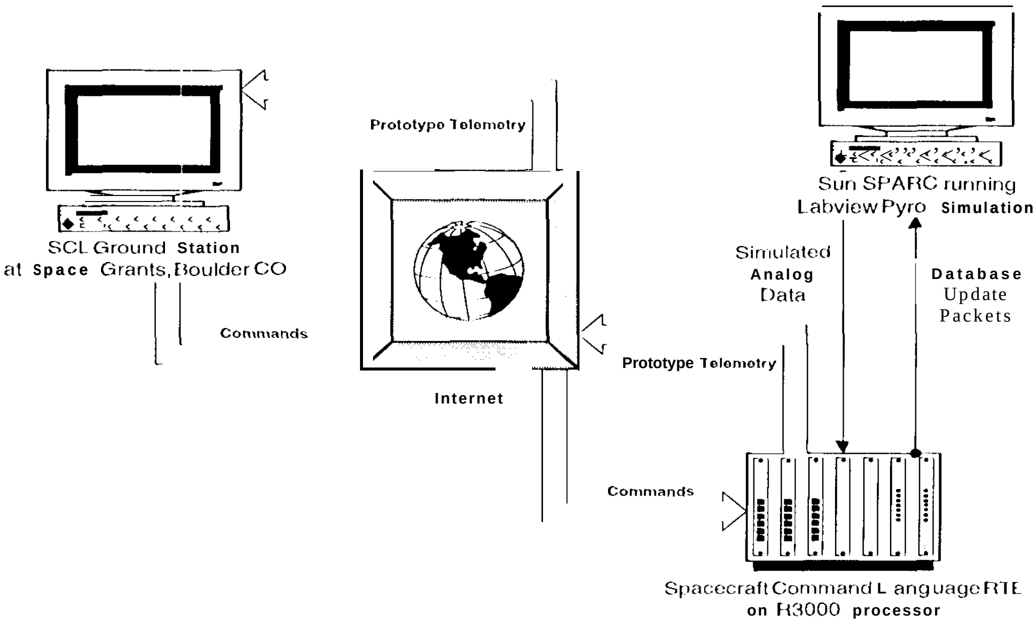

FIGURE 4. Distributed Software Development Configuration

System software Components

The flight software architecture used in prototypes to date is comprised of multi-mission software components offered by the JPL FST and mission-specific software. The flight system is built upon the VXWorks real-time operating system by Wind River Systems. This cross-development environment is hosted on Sun workstations and makes use of the GNU C/C++ cross compilation system. Loading and real-time debugging are performed over the FST local area network. The VXWorks system provides a flexible environment that has facilitated project productivity to date. The mechanism of data flow within the Multimission Components is the Tramel multicast software messaging system. This JPL-developed interprocess communication package "glues" together flight software components.

One of the testbed tasks in FY96 centered around infusing an SCL-based onboard executive into the multi-mission flight software for uplink and downlink. The components of this configuration and associated data flows are shown in Figure 5. The configuration was demonstrated by flowing commands and telemetry between the JPL FST and the JPL Simulated Mission Operations Control Center (SMOCC) as shown in Figure 6. Verifying the uplink and downlink processes were useful in assessing overall fidelity of the flight software prototype. Additionally, this demo was useful as it gave Pluto Express software developers exposure to ground software components used on several ongoing missions at JPL.

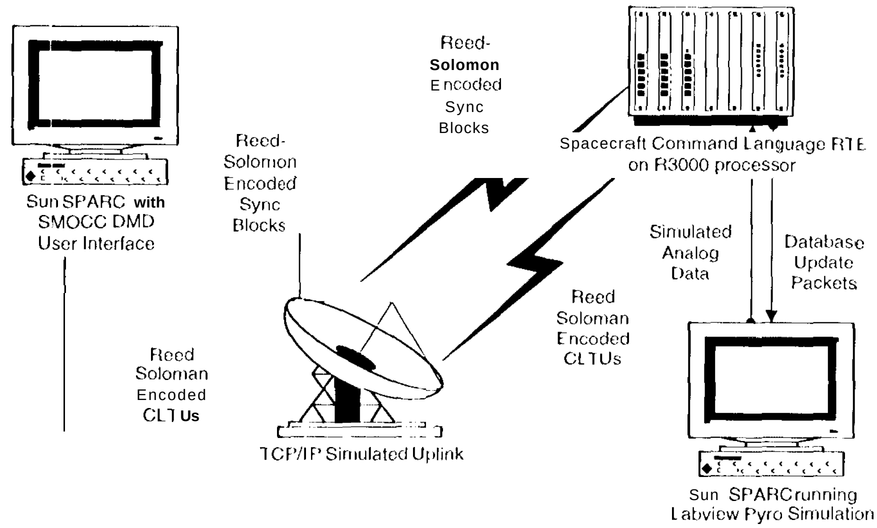

FIGURE 5. Uplink/Downlink Components and Data Flows.

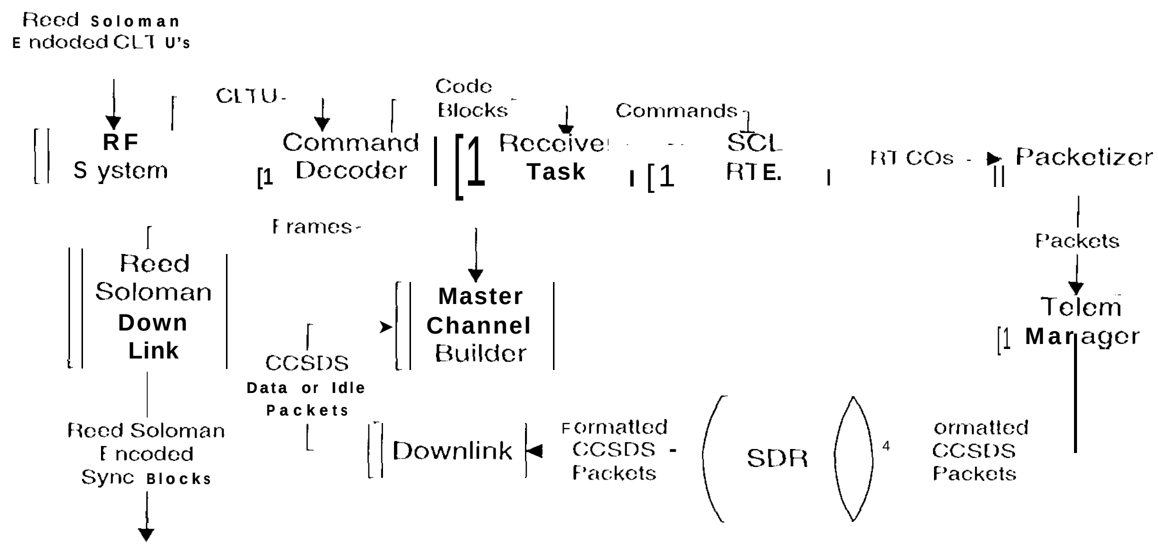

FIGURE 6. SMOCC Demo Architecture.

CONCLUSIONS

Future deep-space and Earth orbiting missions will rely more and more on the accelerated insertion of advanced technologies into flight systems, as a way of reducing total life-cycle system cost, and as a way of sustaining NASA's new role as a national technology leader. In this paper, we described technology insertion for the Pluto Express preproject, as a member of the deep space outer planetary robotic missions which could include a Europa orbiter and Solar Probe. A phased approach to technology insertion was described, which is tightly coupled to the on-going technology validation New Millennium Program. Moreover, two significant technology thrust areas were described: microelectronics systems and advanced software development. Both areas are crucial to the design of low-cost highly autonomous space missions.

Acknowledgments

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